locations. The van stopped at each of 100 points to allow the recording of signal strength, waveform, and spectrum measurements at the van's location.[14] The test points were evenly spaced at intervals of about 3000 ft, and the overall array dimension was about six miles on a side. The test point array thus spanned the entire base station configuration and beyond. The regular spacing of the test points means that some of the points lay in inaccessible locations, in the Potomac or the Tidal Basin, for example. Such points were ignored in the testing, although the presentation of test results had to accommodate the missing data. For the base station component of this test, the same information was recorded at two base stations for each of ten vehicle locations.

3. *Signal strength and waveform observations at mobiles and at base stations;* these essentially have to do with signal integrity. The waveform observed is the SAW correlator output. The van again stopped at each of the 100 test points; each of the five base stations then transmitted 10,000 packets, and the mobile recorded the receptions for later processing. The TransModem also transmitted 10,000 packets, and each of the five base stations recorded these receptions for off-line processing.

Although the test plan included only a few specific tests, the quantity of data recorded was voluminous. The parameters recorded (signal details, TransModem position, and packet errors) allow much flexibility in reducing and displaying the data.

[14] This test used the spectrum analyzer display as an estimator of signal strength expressed in absolute power units (dBm). The waveform observed was the SAW correlator output, and the spectrum analyzer measured signals across the receiver's RF bandwidth. The AGC level in the receiver IF strip gave an independent estimate of received signal strength.

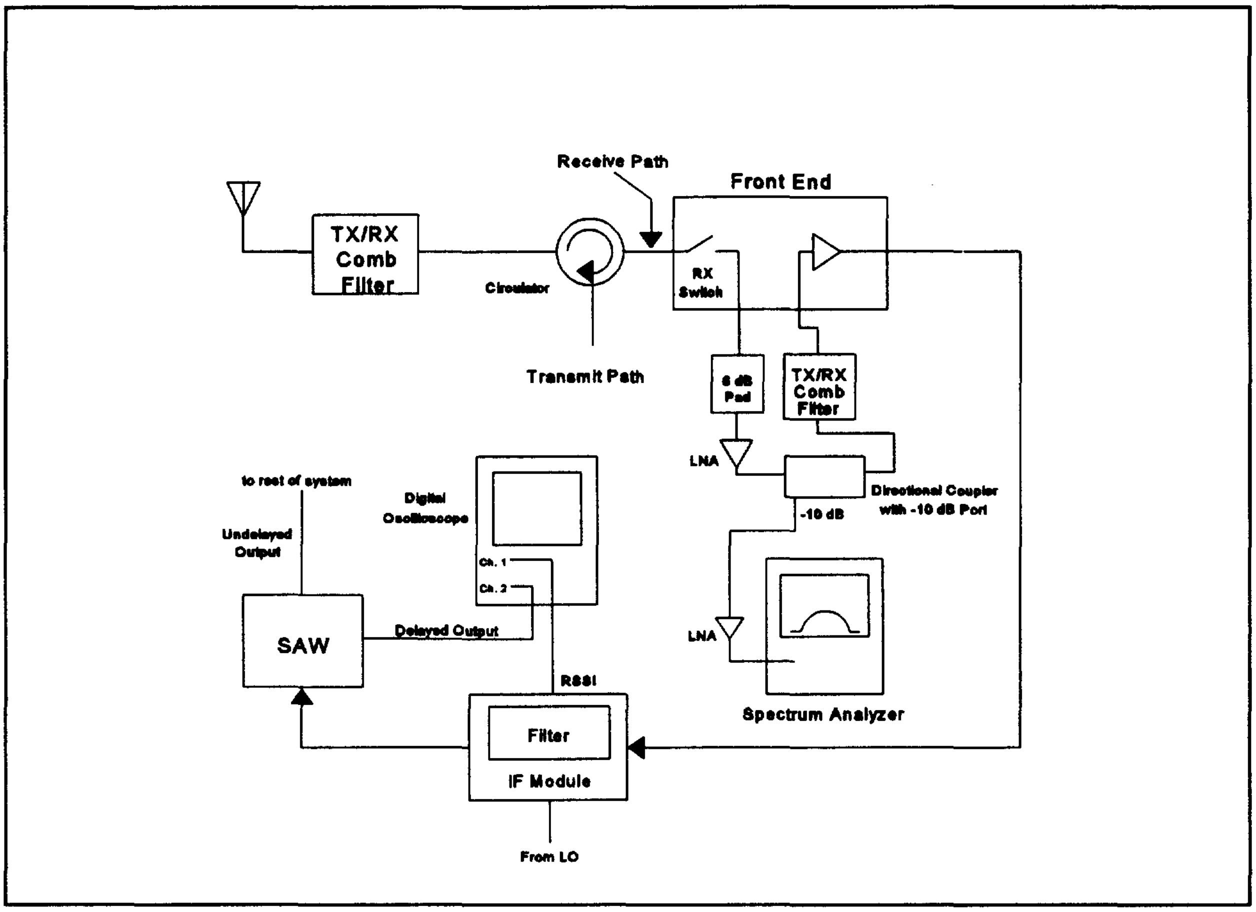

Figure 4 Test equipment configuration

5.2 Conclusions

Test results such as those obtained from the experimental system demonstrate the overall worthiness of the system design. The following two subsections discuss specific test results that illustrate the ability of the Pinpoint system to perform its two principal functions: position determination and digital message transmission.

5.2.1 Position determination

Figure 5 is a diagram showing the positions estimated for the test vehicle as it traveled the route depicted in Figure 3. The system computed four position estimates (using different pairs of base stations) for each TransModem poll, and the figure shows these as four different symbols. At the time of the test, four of the five base stations were operating. Accordingly, the results were obtained from a "minimum configuration" system. For experimental purposes, the raw data were not further processed or corrected.

As the figure demonstrates, the system faithfully tracked the vehicle as it moved along the path. The points are scattered over a range of about two hundred feet at a few of the locations along the test route. As noted above, the route traverses a wide range of signal propagation environments, including areas in which there was a line-of-sight path to most of the base stations to areas in which none were visible from the vehicle. A few of the estimates lie well away from the known route of the vehicle. These points are pathological estimates that likely result from mutilated signals or from reflections that lead to erroneously large time-of-flight readings at one or more base stations. Errors like these may be found in many different types of radionavigation systems and would be rejected by further processing of the position data in a commercially-deployed system. The symbols also exhibit systematic "pairing:" for example, the ■ and ◇ symbols often fall in the same relative positions. (The symbols denote position fixes obtained from different pairs of base stations.) This is probably attributable to differences in calibration between different pairs of base stations. Such differences would lead to systematic offsets in position estimates which can readily be corrected with recalibration or by applying correction factors in the position computation software. These corrections would clearly reduce the scatter of the data in the figure. It is also clear, however, that the position estimation accuracy is more than sufficient to determine the location of the vehicle along the test route. The route is not a long one; its maximum breadth is about 6 km, or less than four miles. Despite the "raw" nature of the data, the relative scatter of the points in the figure is not objectionable for many mobile position-determining applications.

5.2.2 Message transmission reliability

In this test, each of the five base stations transmitted message packets to the fixed TransModem at each of the accessible test locations. At each of the points enclosed by the base station cluster, the TransModem correctly received packets at all accessible points. While analyzing and reducing the data from this test, Pinpoint discovered a signal processing implementation problem that led to an inordinately large number of message rejections. The issue had to do with how the receiver processes the SAW correlator output in the presence of multipath; by modifying the digital processing of this signal, the designers profoundly improved the number of packets received at each point. Even before the adjustment in the signal processing procedures, however, the TransModem reliably received packets from the base station network. This results, as one would expect, from the overall system design, because the messaging function is

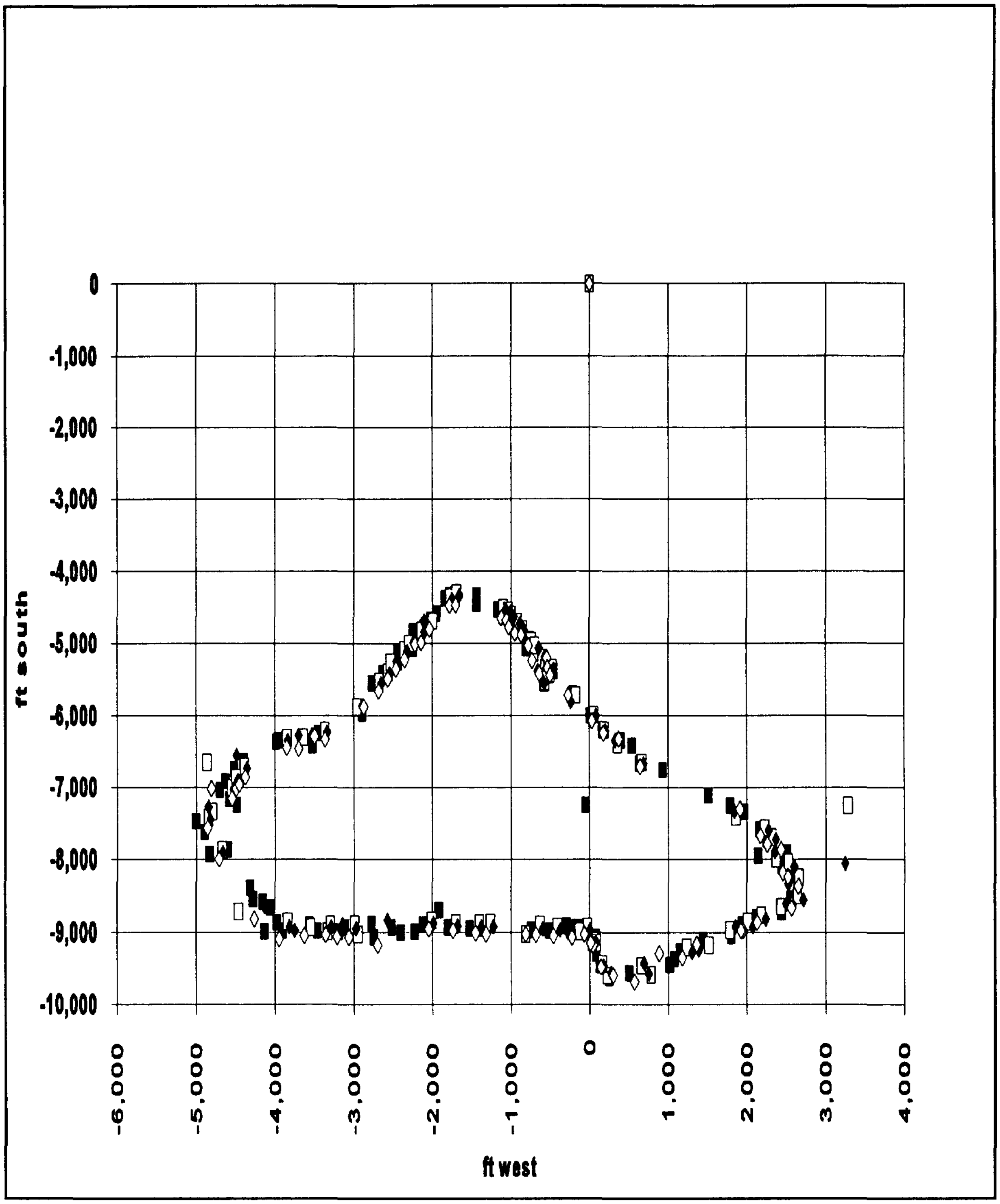

Figure 5 Position estimates for vehicle along test route

necessarily easier to implement than is the position-determining function. In order to estimate a position, at least three base stations must simultaneously correctly receive the TransModem transmission, while, in the messaging case, only one base station need receive a packet correctly.

Thus, position determination "stresses" the system much more than does the messaging function. Also, the messaging function has the advantage of "path diversity" in both the inbound and outbound directions, while the positioning function has somewhat less (although the system will order other base stations to transmit to a given TransModem in a later system cycle if there is no response from a given base station, as noted elsewhere in this report.)

The system operated at least as well in the mobile case. Because the symbol duration is quite short (11 μs), the radio channel is essentially stationary during a symbol period at land vehicle speeds. For example, at 100 mph (147 ft/s), a vehicle would move 0.02 inches during a symbol interval; this is less than two one-thousandths of a wavelength. Furthermore, the test procedure recorded a very large number of data points over all the fixed positions in the test location array, so that one may safely assume that the tests encompassed a sufficiently broad range of propagation conditions to allow the extension of the results to the case in which the TransModem is moving during message reception and transmission. In any case, the results reported clearly demonstrate the ability of the system to perform the messaging function reliably.

5.2.3 Signal strength

Figure 6 shows the signal strength received as a function of distance from the USA Today base station. The points in this graph are processed from the raw data recorded at the fixed points in the test array, as discussed above. The figure thus occasionally shows multiple values at a given distance from the base station, because several of the array points may have been the same distance from the base, although they would lie in different directions from the base.

This figure shows that the received signal level was above -85 dBm, the nominal TransModem receiver sensitivity, at all but five points in the array. Although commercial TransModems are expected to have better sensitivity, the interference levels in the band are expected to create a noise floor of about -85 dBm. Hence, the test system is representative. The data are scattered widely over the chart, although the scatter cloud generally shows a rapid decrease in signal strength with distance, as one would expect. The degree of scatter is large, owing to the fact that the test area encompassed a wide range of propagation conditions, as noted above; some of the points may have lain in deep coverage nulls, spreading the data points even more.

The data show that the vast majority of the points received signals well above the receiver sensitivity, a fact that confirms the proper placement of this base station for adequate coverage within the system boundary. A plot such as this one generally reflects conditions of the particular network implementation and not the fundamental system architecture. For proper system operation, base stations must be located suitably, antennas properly selected, and transmitter power levels correctly adjusted to ensure that coverage levels over as large a percentage as possible of the service area are adequate for the known mobile receiver characteristics. It is equally important for the system designers to ensure that the base station placement and antenna selection accommodates the mobile transmitters' effective radiated power levels. Thus, the figure illustrates that coverage is adequate for proper two-way operation at ranges of up to about three miles from the USA Today site, a distance that easily includes the interior of the base station array in the test system configuration.

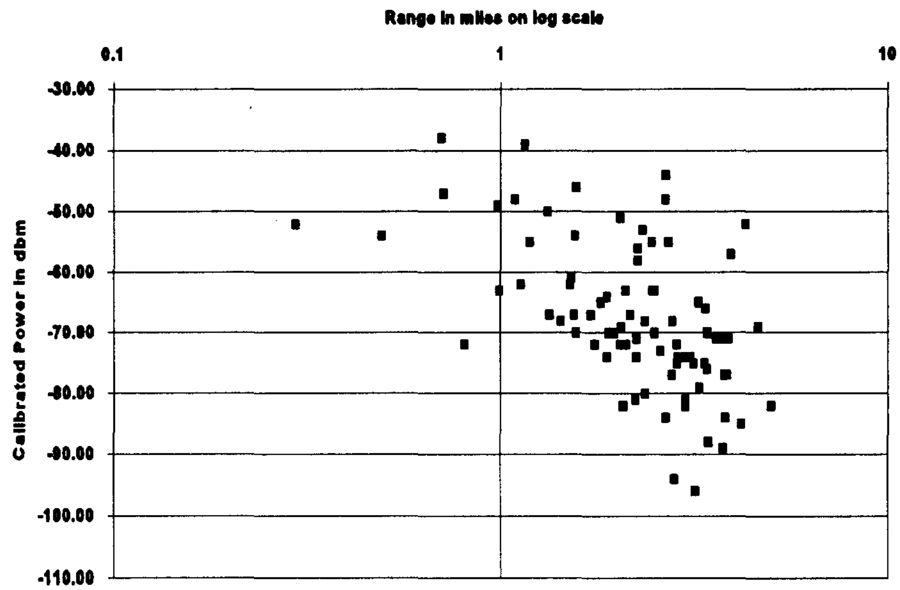

Figure 6 Strength of USA Today base station signal received by mobile

5.2.4 Conclusions

The test results as reported for the purposes of this demonstrate that the Pinpoint system effectively determines the location of moving and stationary vehicles in a manner useful to fleet operators and other potential users who need to know the current location of vehicles and further may need to pass messages between a central point and any or all of the vehicles in the fleet. The tests also show that the messaging and locating functions operate effectively for moving as well as stationary vehicles.

6.0 Compatibility testing

Under current FCC licensing practices, wide-area (such as Pinpoint's) and local-area AVM systems share the same spectrum. To assess the practicality of continued licensing on this basis, Pinpoint and Amtech Corporation jointly tested their systems in the Washington, D.C., area during the summer and fall of 1993. Amtech develops radio frequency electronic identification systems for various AVM applications, including automatic toll collection; their systems operate under Part 90 in the 902-928 MHz band.

In the first test, the two companies set up equipment about one-half mile from Pinpoint's Crystal City base station in a parking lot near National Airport with a line-of-sight path between the base station and the test site. Amtech installed a toll booth system (including a "reader," a transmitter/receiver used to "read" passive tags mounted on vehicles), and Pinpoint operated a van-mounted TransModem in the vicinity of the Amtech equipment. The two systems operated on nearly the same center frequency for the test: 918 MHz for Amtech, and 920 MHz for the Pinpoint equipment. The Pinpoint mobile unit's transmitter developed 35 W; with a 2 dB antenna at a height of 6 ft. When one considers transmission line and other losses, the unit transmitted about 40 W ERP. The base station transmitter operated at 80 W using a 10 dB antenna and radiated about 500 W ERP. Transmitted pulse widths ranged from 0.1 to 2.5 ms at a repetition period of 0.1 to 1 s. The Amtech transmitter operated at a maximum power of 32 dBm, or about 1.6 W, and used 4.5 dB or 10 dB antennas.

The test results showed the following:

1. The two systems operated without interaction when the Pinpoint mobile unit was more than about one-fourth to one-half mile from the Amtech reader;

2. When the Pinpoint mobile transmitted from points between about five hundred feet and one-fourth to one-half mile from the Amtech reader, the Amtech data recording equipment occasionally detected the Pinpoint transmitter's signals. Nonetheless, the Amtech system could still read tags successfully, because a Pinpoint TransModem transmits only infrequently and for very short durations, and the Amtech system interrogates vehicle tags multiple times during a particular transaction. The inherent redundancy in the system design thus accommodates occasional missed data, which could result from any of several effects, including radio frequency interference.

3. When the Pinpoint mobile was within about five hundred feet of the Amtech reader and the Amtech system was transmitting (the Amtech reader transmits only when vehicles are present), the Amtech equipment again occasionally detected the Pinpoint signals, and vice versa. When the Pinpoint vehicle was within fifty to about one hundred feet of the Amtech reader, it did not receive signals from the base station and hence would not respond to polls. Pinpoint concluded that this is not harmful to its overall operation, because the area in which the base station transmission could not be received is quite

small, and the system could track the mobile into the area of interference and mark its position until it moved away from the interfering transmitter. At these distances, 50 to 100 feet, Amtech again found that its system operations were not affected.

Amtech and Pinpoint repeated the tests at another location, Lady Bird Johnson Park, in October with the same equipment configuration used in the August tests. The results were essentially the same as those obtained from the earlier test: neither system detected debilitating interference from the other.

The antenna in use sat about seven feet above the road surface and pointed across the roadway, as shown in Figure 7. The Pinpoint equipment first detected interfering signals at a distance of 198 ft from the 10 dB antenna when it traveled toward the Amtech transmitter; it continued to receive interference until it was 88 ft beyond the Amtech antenna. The interference region was smaller when the Amtech transmitter used the 4.5 dB antenna, as one would expect: the interference region extended from 105 ft in front of the Amtech transmitter to 14 ft behind. Figure 7 also shows the interference regions.

The interference the TransModem received in the near vicinity of an operating Amtech transmitter is no greater a concern than it would be if missed polls resulted from signal blockage or other phenomena. Any mobile communications system will have "holes," or small areas having substandard signal strengths, in its coverage area, and a digital messaging system, such as Pinpoint's, accommodates these coverage gaps by retransmitting signals. The adaptive design of the ARRAY network further improves the effective system coverage by assigning different base stations to transmit to a TransModem when it travels into an area obstructed from the base station it has been receiving, as discussed earlier. Installation of new ARRAY network base stations can offset any effects resulting from the introduction of new potential sources of interference in the local environment.

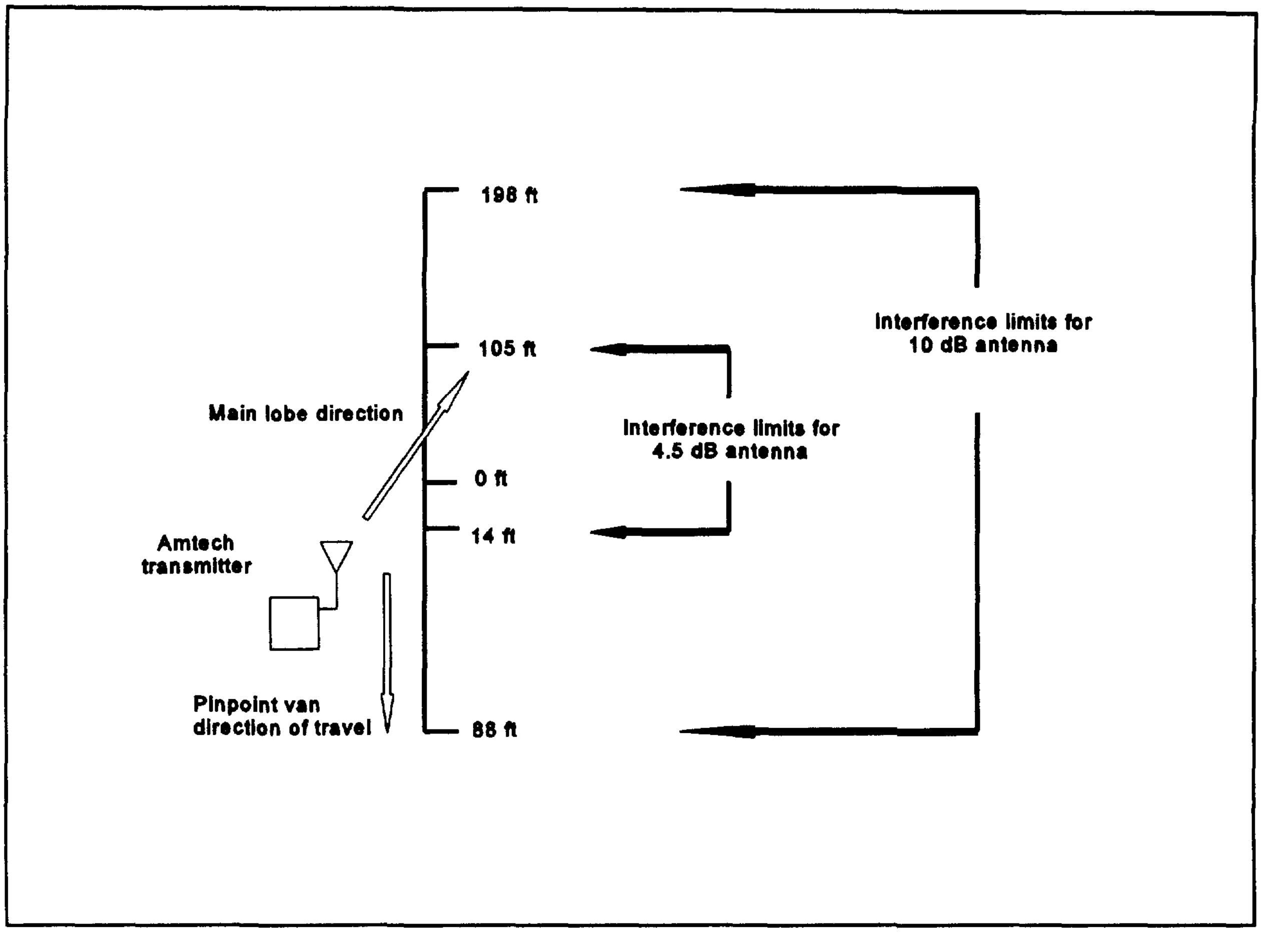

Figure 7 Interference regions in Amtech/Pinpoint compatibility tests

7.0 Conclusions

The Pinpoint system is well-conceived and competently designed. Pinpoint's developers have produced a very robust system design that uses the radio spectrum efficiently through integrated messaging and position determination. The principal conclusions of the analysis of the system design and experimental system test results are as follows:

1. The ARRAY network, including the base stations, Network Control Center, and subscriber TransModems, work as designed: the system as a whole effectively computes vehicle locations, whether the vehicles are moving or stopped, and allows reliable message transmission to and from TransModems using the same frequency band as the ranging function. The base station and TransModem designs are impressively simple, so that commercial versions of the network components should be quite affordable and service costs low.

2. The time-division-multiplexed nature of the basic system over-the-air protocol inherently allows time sharing with other competing wide-area systems using the same spectrum. The system design is therefore basically "friendly" to cooperative sharing arrangements and can accommodate such without redesign.

3. The compatibility tests show that the Pinpoint network can also coexist with local systems operating in the same band without causing or receiving unacceptable levels of interference. Even when Pinpoint equipment operated in the very near vicinity of transmitters and receivers operating at the same frequency but in a different system, the interference levels to both systems were insignificant and easily accommodated by the systems' over-the-air protocols and data processing components.

The Pinpoint network architecture adapts itself to different market coverage requirements through its dynamic "cluster" configuration. By defining a "cluster" as a set of base stations that receive a particular TransModem's transmission at a given point in time, the system design inherently provides good coverage for both messaging and ranging without requiring complicated analyses of frequency re-use patterns and the control structure complexity that would result from the rigid definition of clusters. Similarly, by computing position estimates using the time-of-arrival information from the base stations that are best situated for accurate position determination, the system architecture fundamentally avoids many of the geometric accuracy difficulties that often plague other, more inflexible, system designs.

The Network Control Center's interfaces are clearly defined to allow customers of network services to connect their host applications processors with the ARRAY network and allow their applications to request and obtain information from their fleet members using a simple basic set of messages. The NCC's responsibilities for computing positions and determining received message integrity allow it to communicate with user applications at a high level, and features such as group polling improve the ability of the overall system to handle large numbers of users with disparate applications needs.